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Heon Lee, et al.

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# MAGNETIC TUNNEL JUNCTION DEVICE WITH A COMPOSITIONALLY MODULATED ELECTRODE

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**Attorney**

**Trueman H. Denny III**

**Inventorship:**

**Heon L e**
**Manish Sharma**

# MAGNETIC TUNNEL JUNCTION DEVICE WITH A COMPOSITIONALLY MODULATED ELECTRODE

## FIELD OF THE INVENTION

The present invention relates generally to a magnetic tunnel junction device including a compositionally modulated electrode and a method of fabricating the same. More specifically, the present invention relates to a magnetic tunnel junction device including a compositionally modulated electrode in which the electrode includes a high resistivity region operative to generate joule heating in response to a current flowing in the electrode. The high resistivity region can be fabricated using a process including a plasma oxidation, a plasma nitridation, a plasma carburization, or an alloying process.

## BACKGROUND OF THE ART

Magnetic Random Access Memory (MRAM) is an emerging technology that can provide an alternative to traditional data storage technologies. MRAM has desirable properties including fast access times like DRAM and non-volatile data retention like hard disc drives. MRAM stores a bit of data (i.e. information) as an alterable orientation of magnetization in a patterned thin film magnetic element that is referred to as a data layer, a sense layer, a storage layer, or a data film. The data layer is designed so that it has two stable and distinct magnetic states that define a binary one ("**1**") and a binary zero ("**0**"). Although the bit of data is stored in the data layer, many layers of carefully controlled magnetic and dielectric thin film materials are required to form a complete magnetic memory element. One prominent form of magnetic memory element is a spin tunneling device. The physics of spin tunneling is complex and good literature exists on the subject of spin tunneling.

In **FIG. 1a**, a prior magnetic tunnel junction device **201** includes a data layer **202** and a reference layer **204** that are separated by a thin tunnel barrier layer **206**. Typically the tunnel barrier layer **206** has a thickness that is less than about 2.0 nm, for

example. In a tunneling magnetoresistance (TMR) structure the tunnel barrier layer **206** is an electrically non-conductive dielectric material such as aluminum oxide ($Al_2O_3$), for example. Whereas, in a giant magnetoresistance (GMR) structure the tunnel barrier layer **206** is a thin layer of an electrically conductive material such as copper (**Cu**), for example.

The reference layer **204** has a pinned orientation of magnetization **208**, that is, the pinned orientation of magnetization **208** is fixed in a predetermined direction and does not rotate in response to an external magnetic field. In contrast the data layer **202** has an alterable orientation of magnetization **203** that can rotate between two orientations in response to an external magnetic field.

In **FIG. 1b**, when the pinned orientation of magnetization **208** and the alterable orientation of magnetization **203** point in the same direction (i.e. they are parallel to each other) the data layer **202** stores a binary one (“**1**"). On the other hand, when the pinned orientation of magnetization **208** and the alterable orientation of magnetization **203** point in opposite directions (i.e. they are anti-parallel to each other) the data layer **202** stores a binary zero (“**0**").

In **FIG. 1c**, the prior magnetic tunnel junction device **201** is typically positioned at an intersection of two orthogonal conductors **205** and **207**. The conductors (**205, 207**) are also referred to as electrodes, write lines, row conductors, column conductors, word lines, and bit lines. For instance, the conductor **205** can be a word line and the conductor **207** can be a bit line. A bit of data is written to the prior magnetic tunnel junction device **201** by generating two magnetic fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ that are in turn generated by currents $\mathbf{i_Y}$ and $\mathbf{i_X}$ flowing in the conductors **207** and **205** respectively. For purposes of illustration, the current $\mathbf{i_X}$ is depicted as flowing in a direction parallel to a x-axis **X** and the current $\mathbf{i_Y}$ is depicted as flowing in a direction parallel to a y-axis **Y**.

The magnetic fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ cooperatively interact with the data layer **202** to rotate the alterable orientation of magnetization **203** from a current orientation to a new orientation. Therefore, if the current orientation is parallel (i.e. positive x-direction on the x-axis) with the pinned orientation of magnetization **208** such that a binary **"1"** is stored in the data layer **202**, then the magnetic fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ will rotate the alterable orientation of magnetization **203** to an anti-parallel orientation (i.e. negative x-direction on the x-axis) such that a binary **"0"** is stored in the data layer **202**.

In **FIG. 2**, the prior magnetic tunnel junction device **201** can be positioned in an array **301** of similar prior magnetic tunnel junction devices **201** that are also positioned at an intersection of a plurality of conductors (**207, 205**) that are arranged in rows and columns. The configuration depicted is typical of prior MRAM devices. For purposes of illustration, in **FIG. 2**, the conductors **207** are bit lines and the conductors **205** are word lines. The conductors (**205, 207**) need not be in direct contact with the prior magnetic tunnel junction devices **201**. Typically, one or more layers of material separate the conductors (**205, 207**) from the data layer **202** and the reference layer **204**.

A bit of data is written to a selected one of the prior magnetic tunnel junction devices **201** that is positioned at an intersection of a word and bit line by passing the aforementioned currents $\mathbf{i_Y}$ and $\mathbf{i_X}$ through the word and bit lines. During a normal write operation the selected magnetic tunnel junction device **201** will be written to only if the combined magnetic fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ are of a sufficient magnitude to switch (i.e. rotate) the alterable orientation of magnetization **203** of the prior magnetic tunnel junction device **201**.

One disadvantage of the prior magnetic tunnel junction device **201** is that a coercivity $\mathbf{H_C}$ of a material of the data layer **202** is relatively high at a typical operating temperature of the prior magnetic tunnel junction device **201**. In **FIG. 3**, a curve **300** depicts a magnitude of a switching field (i.e. $\mathbf{h_X}$ and $\mathbf{h_Y}$) required to rotate the alterable

orientation of magnetization **203** as a function of a temperature **T mp** (on an x-axis) of the data layer **202** and a coercivity $\mathbf{H_C}$ (on a y-axis) of the data layer **202**. The lower the temperature **T mp** the higher the coercivity $\mathbf{H_C}$. Accordingly, at a typical operating temperature of $\mathbf{T_1}$, the data layer **202** has a coercivity $\mathbf{H_C}$ at $\mathbf{T_1}$ that results in a switching field $\mathbf{S_H}$ that is relatively high on the curve **300**.

Disadvantages to the high switching field $\mathbf{S_H}$ include high currents for $\mathbf{i_Y}$ and $\mathbf{i_X}$ in order to generate the required magnitude of the switching field $\mathbf{S_H}$ and those high currents require large driver circuits to supply the current. Large driver circuits increase an areal density of the MRAM and generate waste heat. Moreover, a major disadvantage to the high switching field $\mathbf{S_H}$ is that a magnitude of the fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ that comprise the switching field $\mathbf{S_H}$ are such that non-selected magnetic tunnel junction devices **201** in the array **301** of **FIG. 2** can have their respective alterable orientation of magnetization **203** switched by the fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ during a write operation to a selected magnetic tunnel junction device **201**. As a result, data stored in the array **301** can be corrupted. The effect of the fields $\mathbf{h_X}$ and $\mathbf{h_Y}$ on non-selected magnetic tunnel junction devices **201** is referred to as a half-select margin. Ideally, only the data in the selected magnetic tunnel junction device **201** is written to during a write operation.

Consequently, there exists a need for a magnetic tunnel junction device in which a temperature of a data layer is increased during a write operation to the magnetic tunnel junction device so that a coercivity of the data layer is reduced and a magnitude of a switching field necessary to write data to the data layer is also reduced.

## SUMMARY OF THE INVENTION

The magnetic tunnel junction device of the present invention solves the aforementioned disadvantages of the prior magnetic tunnel junction devices. An electrode in electrical communication with a data layer of the magnetic tunnel junction device includes a high resistivity region that has a higher resistivity than the electrode. Consequently, joule heating occurs in the high resistivity region when a current flows through the electrode. The heating raises a temperature of the data layer thereby reducing a coercivity of the data layer. The reduced coercivity reduces a magnitude of a switching filed necessary to rotate an alterable orientation of magnetization of the data layer during a write operation to the data layer.

Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the present invention.

## BRIEF DESCRIPTION OF THE DRAWINGS

**FIG. 1a** is a profile view depicting a prior magnetic tunnel junction device.

**FIG. 1b** is a profile view depicting data storage in a prior magnetic tunnel junction device.

**FIG. 1c** is a profile view depicting a pair of write conductors that cross the prior magnetic tunnel junction device.

**FIG. 2** is a profile view of an array of prior magnetic tunnel junction devices positioned between a plurality of row and column conductors.

**FIG. 3** is a graph depicting a high coercivity and a high switching field for the prior magnetic tunnel junction device.

**FIG. 4** is a graph depicting a low coercivity at a high temperature for a magnetic tunnel junction device with a compositionally modulated electrode.

**FIG. 5** is a cross-sectional view depicting a magnetic tunnel junction device with a compositionally modulated electrode.

**FIG. 6** is a profile view of an array of magnetic tunnel junction devices with compositionally modulated electrodes.

**FIG. 6a** is a top plan view depicting a high resistivity region of an electrode relative to a data layer of a magnetic tunnel junction device.

**FIG. 6b** is a profile view depicting a high resistivity region of a compositionally modulated electrode.

**FIG. 7** is a flow diagram depicting a method of fabricating a magnetic tunnel junction device with a compositionally modulated electrode.

**FIG. 8** is a flow diagram depicting an alternative method of fabricating a magnetic tunnel junction device with a compositionally modulated electrode.

**FIGS. 9a** through **9e** are cross-sectional views depicting fabrication of a magnetic tunnel junction device with a compositionally modulated electrode according to the method of **FIG. 7**.

**FIGS. 10a** through **10f** are cross-sectional views depicting fabrication of a magnetic tunnel junction device with a compositionally modulated electrode according to the method of **FIG. 8**.

## DETAILED DESCRIPTION

In the following detailed description and in the several figures of the drawings, like elements are identified with like reference numerals.

As shown in the drawings for purpose of illustration, the present invention is embodied in a magnetic tunnel junction device with a compositionally modulated electrode, and a method of fabricating a magnetic tunnel junction device with a compositionally modulated electrode.

A magnetic tunnel junction device with a compositionally modulated electrode includes a reference layer that includes a pinned orientation of magnetization, a first electrode in electrical communication with the reference layer, a data layer including an alterable orientation of magnetization, a tunnel barrier layer positioned intermediate between the data layer and the reference layer, and an electrode in electrical communication with the data layer and including a first resistivity. The electrode includes a high resistivity region that includes a second resistivity. The second resistivity is higher than the first resistivity.

The high resistivity region is disposed in the electrode and is positioned substantially over the data layer. Joule heating is generated in the high resistivity region in response to a write current flowing in the electrode during a write operation to the data layer (i.e. to change the bit of data from a "**0**" to a "**1**" or vice-versa). The joule heat is thermally conducted into the data layer where it heats up the data layer and reduces a coercivity of the data layer. As a result, a magnitude of a switching field operative to rotate the alterable orientation of magnetization is reduced. The coercivity of the data layer is a function of temperature and as a temperature of the data layer increases the coercivity of the data layer decreases.

The reduction in coercivity is particularly important during a write operation to the data layer where write currents flowing in the electrode and the first electrode generate

magnetic fields that cooperatively interact to create a switching field that causes the alterable orientation of magnetization to rotate (i.e. flip) from a first stable orientation to a second stable orientation so that a state of the data stored in the data layer is changed from a logic "**0**" to a logic "**1**", or vice-versa. One advantage of the magnetic tunnel junction device with a compositionally modulated electrode is that the high resistivity region generates the joule heat that heats up the data layer during the write operation and reduces the coercivity of the data layer during the write operation. The reduction in coercivity also reduces a magnitude of the switching field necessary to rotate the alterable orientation of magnetization.

A method of fabricating a compositionally modulated electrode in a magnetic tunnel junction device includes depositing **62** a mask layer on a surface of a previously fabricated electrode of the magnetic tunnel junction device, patterning **64** a plasma mask in the mask layer, forming **66** the plasma mask in the mask layer, and forming **68** a high resistivity region that extends inward of the surface of the electrode using a plasma oxidation process, a plasma nitridation process, or a plasma carburization process, and removing **70** the plasma mask.

Alternatively, a method of fabricating a compositionally modulated electrode in a magnetic tunnel junction device includes depositing **82** an alloy layer on a surface of a previously fabricated electrode of the magnetic tunnel junction device, depositing **84** a mask layer on the alloy layer, patterning **86** the mask layer to form an etch mask on the alloy layer, etching **88** the alloy layer to form an alloy patch on the surface of the electrode, removing **90** the etch mask, and alloying **92** the alloy patch with the electrode by applying heat to form a high resistivity region that extends inward of the surface of the electrode.

In **FIG. 5**, a magnetic tunnel junction device **10** includes a data layer **11** including an alterable orientation of magnetization **M2**. In the MRAM art, the data layer **11** is also referred to as a sense layer, a storage layer, and a free layer. The data layer **11** stores a bit of information (i.e. a "**1**" or a "**0**") as one of two stable orientations of the alterable

orientation of magnetization **M2**. A reference layer **15** including a pinned orientation of magnetization **M1** and a first electrode **19** in electrical communication with the reference layer **15**. In the MRAM art, the reference layer **15** is also referred to as a pinned layer or a pinning layer. A tunnel barrier layer **13** is positioned intermediate between the data layer **11** and the reference layer **15**. Depending on a topology of the magnetic tunnel junction device **10**, the tunnel barrier layer **13** may or may not be in direct contact with the data layer **11** and/or the reference layer **15**. For purposes of illustration only, the tunnel barrier layer is depicted as being in direct contact with the data layer **11** and the reference layer **15**. An electrode **17** is in electrical communication with the data layer **11** and the electrode **17** includes a first resistivity denoted as $\rho_L$. The electrode **17** also includes a high resistivity region **18** that includes a second resistivity $\rho_H$ that is higher than the first resistivity $\rho_L$ (i.e. $\rho_H > \rho_L$). The high resistivity region **18** is disposed in the electrode **17** and is positioned substantially over the data layer **11**. The high resistivity region **18** is operative to generate a joule heat $\mathbf{J_H}$ in response to a write current $I_Y$ flowing in the electrode **17**. The joule heat $\mathbf{J_H}$ is thermally conducted into the data layer **11** and heats the data layer **11** so that a coercivity $\mathbf{H_C}$ of the data layer **11** is reduced.

In **FIG. 4**, a curve **40** depicts a magnitude of a switching field necessary to rotate the alterable orientation of magnetization **M2** of the data layer **11** as a function of a coercivity $\mathbf{H_C}$ (increasing along a y-axis) and a temperature **T** (increasing along a x-axis) of the data layer **11**. At a nominal temperature $\mathbf{T_N}$, the data layer **11** has a nominal coercivity $\mathbf{H_N}$ and a nominal magnitude of a switching field $\mathbf{S_N}$ on the curve **40**.

For instance, the nominal temperature of $\mathbf{T_N}$ can be a room temperature (e.g. about 25 °C) or the nominal temperature of $\mathbf{T_N}$ can be an operating temperature of the magnetic tunnel junction device **10** or an MRAM devices that includes the magnetic tunnel junction device **10**. Accordingly, at the nominal temperature $\mathbf{T_N}$ the coercivity $\mathbf{H_C}$ of the data layer **11** is the nominal coercivity $\mathbf{H_N}$, which is relatively high on the coercivity

$\mathbf{H_C}$ axis and the magnitude of the switching field is the nominal switching field $\mathbf{S_N}$, which is also relatively high on the switching field curve **40** as illustrated by the solid lines intersecting the curve **40** at $\mathbf{S_N}$.

Because the coercivity $\mathbf{H_C}$ of the data layer **11** decreases as temperature **T** increases, as illustrated by the curve **40**, the heating up of the data layer **11** by the joule heat $\mathbf{J_H}$ operates to increase the temperature **T** of the data layer **11** to a higher temperature $\mathbf{T_J}$ that is higher than the nominal temperature $\mathbf{T_N}$. Consequently, at the higher temperature $\mathbf{T_J}$, the coercivity $\mathbf{H_C}$ of the data layer **11** is reduced to a lower coercivity $\mathbf{H_J}$ with a resulting reduction in a magnitude of the switching field as depicted by the intersection of the heavy dashed lines with the switching field curve **40** at the lower switching field $\mathbf{S_J}$. Accordingly, the switching field $\mathbf{S_J}$ at the higher temperature $\mathbf{T_J}$ is less than the nominal switching field $\mathbf{S_N}$ at the lower temperature $\mathbf{T_N}$ (that is at $\mathbf{T_N}$: $\mathbf{S_J} < \mathbf{S_N}$).

The high resistivity region **18** need not be perfectly centered or symmetrically centered over the data layer **11**; however, it is desirable for the high resistivity region **18** to be positioned in relation to the data layer **11** so that the joule heat $\mathbf{J_H}$ is efficiently transferred to the data layer **11**, heats up the data layer **11**, and the coercivity $\mathbf{H_C}$ of the data layer **11** is reduced as described above.

The joule heat $\mathbf{J_H}$ is generated because the second resistivity $\rho_H$ of the high resistivity region **18** increase a resistance to the flow of electrons in the electrode **17** and the write current $I_Y$ flowing through the electrode **17** cause waste heat to be generated in the high resistivity region **18** due to the second resistivity $\rho_H$ being higher than the first resistivity $\rho_L$ of the electrode **17** (i.e. $\rho_H > \rho_L$). Accordingly, the joule heat $\mathbf{J_H}$ is proportional to a product of a resistance **R** of the electrode **17** at the high

resistivity region **18** and the write current $I_Y$ such that:

$$\mathbf{J_H} \propto (I_Y)^2 * \mathbf{R}$$

In **FIG. 5**, the switching field $\mathbf{S_J}$ is generated by magnetic fields created by the write currents ($I_Y$, $I_X$) flowing in the electrode **17** and the first electrode **19**. The write current $I_Y$ generates a magnetic field $H_X$ and the write current $I_X$ (flowing in the first electrode **19**) generates a magnetic field $H_Y$. The magnetic fields ($H_Y$, $H_X$) contribute to a portion of the switching field $\mathbf{S_J}$ and cooperatively interact with the alterable orientation of magnetization **M2** and cause the alterable orientation of magnetization **M2** to rotate. In **FIG. 5**, the write current $I_X$ flows through the first electrode **19** and is depicted as flowing into the drawing sheet (i.e. into the page).

Although not depicted in **FIG. 5**, the magnetic tunnel junction device **10** can include a second electrode **21** (see **FIGS. 9e** and **10f**) that is positioned adjacent to the first electrode **19** and is electrically isolated from the first electrode **19**. For example, the second electrode **21** can be separated from the first electrode **19** by a dielectric material such as silicon oxide ($\mathbf{SiO_2}$). The second electrode **21** is operative to generate a portion $H_Y$ of the switching field $\mathbf{S_J}$ in response to the write current $I_X$ flowing in the second electrode **21**. When the second electrode **21** is used, the electrode **17** and the first electrode **19** can be used to sense the state of the alterable orientation of magnetization **M2** during a read operation to the magnetic tunnel junction device **10** so the data stored in the data layer **11** can be read. The electrode **17** and the second electrode **21** are used to write data to the data layer **11** in response to the aforementioned write currents ($I_Y$, $I_X$).

As will be described below in reference to a method for fabricating a compositionally modulated electrode in a magnetic tunnel junction device, the high resistivity region **18** can be made from a material including but not limited to an alloy of

a material of the electrode **17** with a second material, a material that has been oxidized by a plasma oxidation process, a material that has been nitridized by a plasma nitridation process, and a material that has been carburized by a plasma carburization process.

For example, the second material for the high resistivity region **18** can be a metal or a metal alloy that is alloyed with the material of the electrode **17** and results in the high resistivity region **18** having the second resistivity $\rho_H$. As another example, the electrode **17** can be made from tungsten (**W**) and the second material can be a metal that is alloyed with the tungsten to form the high resistivity region **18**.

In **FIG. 6**, a plurality of the magnetic tunnel junction devices **10** can be arranged in an array **100** in which each magnetic tunnel junction device **10** is positioned at an intersection of an electrode **17** and a first electrode **19**. For example, the electrodes **17** can be arranged in columns and the first electrodes **19** can be arranged in rows, or vice-versa. The array **100** can be carried by a MRAM device used for data storage. A magnetic tunnel junction device **10** is selected for a write operation to its data layer **11** by passing the write currents ($I_Y$, $I_X$) through the respective electrodes (**17, 19**) that cross the selected magnetic tunnel junction device **10** as denoted by a selected magnetic tunnel junction device **10'**. The high resistivity region **18'** of the selected magnetic tunnel junction device **10'** generates joule heat $\mathbf{J_H}$ as described above. For purposes of illustration only, a X-Y axis **120** is shown to depict the current $I_X$ as flowing along a x-axis and the current $I_Y$ as flowing along a y-axis.

In **FIG. 6a**, the data layer **11** can have a width **W** and a height **H** that may not be identical to a width **W**$\rho$ and a height **H**$\rho$ of the high resistivity region **18**. For example, the width **W**$\rho$ and the height **H**$\rho$ of the high resistivity region **18** can be smaller than the width **W** and the height **H** of the data layer **11**. Although for purposes of illustration the high resistivity region **18** is depicted as being symmetrically positioned relative to the

data layer **11**, the actual position of the high resistivity region **18** need not be symmetrical relative to the data layer **11** and will depend on factors such as alignment errors that occur during the microelectronic fabrication processes that are used to fabricate the magnetic tunnel junction devices **10** and variations in the alloying and plasma processes as will be described below.

In **FIG. 6b**, the high resistivity region **18**, the electrode **17**, and the data layer **11** are depicted in greater detail. The high resistivity region **18** extends inward of a surface **17s** of the electrode **17** by a predetermined depth $\mathbf{d_O}$. Preferably, the high resistivity region **18** does not extend all the way through a thickness $\mathbf{t_O}$ of the electrode **17** (i.e. to a bottom surface **17b**) so that the high resistivity region **18** is offset from the bottom surface **17b** by an offset distance $\mathbf{h_O}$. The offset distance $\mathbf{h_O}$ may be necessary to prevent the high resistivity region **18** from extending to the thin film layers in the magnetic tunnel junction stack **10** (e.g. the data layer **11**) and damaging those layers due to the process and/or materials used to compositionally modulate the electrode **17** to form the high resistivity region **18**.

In **FIG. 9a** and referring to a method of fabricating a compositionally modulated electrode in a magnetic tunnel junction device depicted in **FIG. 7**, at a stage **62**, a mask layer **25** is deposited on a surface **17s** of a previously fabricated electrode **17** of the magnetic tunnel junction device **10**. The electrode **17** is in electrical communication with the data layer **11** either by direct contact (see **FIG. 5**) or by an intermediate structure such as a via **17v**, a damascene contact, or the like.

Prior to a start of the method at a stage **60**, the various thin film layers of material that comprise the magnetic tunnel junction device **10** (i.e. **11, 13, 15, 17, 17v, 19, 21** and **31**) have been previously fabricated in a process order $\mathbf{D_O}$. Moreover, the magnetic tunnel junction device **10** is not limited to the layers of material described herein. For instance, it is well known in the MRAM art to include other layers of material such as cap layers, pinning layers, seed layers, and antiferromagnetic layers, just to name a few. Unless otherwise noted, the layers of material that comprise the magnetic

tunnel junction device **10** will be collectively denoted as a stack **20**. In **FIGS. 9a** through **10f**, the stack **20** is formed in a layer of dielectric material **31** and the layer of dielectric material **31** can be supported by a substrate (not shown) such as a semiconductor wafer or a silicon (**Si**) wafer. The dielectric material **31** can be a material including but not limited to silicon oxide ($SiO_2$), silicon nitride ($Si_3N_4$), a tetraethylorthosilicate (**TEOS**), and a doped tetraethylorthosilicate (**TEOS**).

Accordingly, the electrode **17** has already been deposited or otherwise formed in the process order $D_O$. As described above, the electrode **17** has a first resistivity $\rho_L$. The mask layer **25** can be a photoresist material or any other material that will serve as a suitable mask in a plasma oxidation, plasma nitridation, or plasma carburization process.

At a stage **64**, a pattern for a plasma mask is patterned in the mask layer **25**. Lithographic patterning process that are well understood in the microelectronics art can be used to pattern the mask layer **25**. For example, the mask layer **25** can be made from a photoresist material and exposed to a light **L** through a photo mask (not shown) to transfer a pattern for the plasma mask to the mask layer **25**.

In **FIG. 9b**, at a stage **66**, a plasma mask (not shown) is formed in the mask layer **25**. For example, if a photoresist material is used, then the mask layer **25** can be developed in a solvent to remove only those portions of the mask layer **25** that were exposed to the light **L**. On the other hand, the mask layer **25** can be wet or dry etched **E** to form the plasma mask. Preferably, an anisotropic/directional etch process such as a reactive ion etch (RIE) is used to etch the mask layer **25** to form the plasma mask.

In **FIG. 9c**, a plasma mask **27** is formed on the electrode **17** and portions of the surface **17s** of the electrode **17** are not covered by the plasma mask **27**. Therefore, a portion **17** of the surface **17s** is exposed by the plasma mask **27**. At a stage **68**, a high resistivity region **18** is formed in the electrode **17** by exposing the portion **17** to a

plasma process **P** that modulates a composition of the electrode **17** in the high resistivity region **18**. The plasma process **P** can be a process including but not limited to a plasma oxidation process, a plasma nitridation process, and a plasma carburization process. The plasma process **P** modulates the composition of the electrode **17** so that the high resistivity region **18** includes a second resistivity $\rho_H$ that is higher than the first resistivity $\rho_L$ of the electrode **17**.

The plasma process **P** that forms the high resistivity region **18** can be continued until the high resistivity region **18** extends inward of the surface **17s** by a predetermined depth $\mathbf{d_O}$. Process factors such as a time the portion **17e** is exposed to the plasma **P** can be used to set the predetermined depth $\mathbf{d_O}$. Preferably, the predetermined depth $\mathbf{d_O}$ does not extend to a thickness $\mathbf{t_O}$ of the electrode **17**, especially if the plasma process **P** or the compounds such as oxygen ($O_2$), nitrogen ($N_2$), or carbon (**C**) that are used in the plasma process **P** will damage the data layer **11** or the other layers of material in the stack **20**. Alternatively, the plasma process **P** that forms the high resistivity region **18** can be continued until the second resistivity $\rho_H$ of the high resistivity region **18** reaches a predetermined value of resistivity.

In **FIG. 9d**, at a stage **70**, the plasma mask **27** is removed from the surface **17s** of the electrode **17**. For example, a solvent or a plasma ashing process can be used to remove the plasma mask **27**. The high resistivity region **18** is completely formed in the electrode **17** and is positioned substantially over the data layer **11** so that the joule heat $\mathbf{J_H}$ will be thermally conducted into the data layer **11** during a write operation as was described above. Although the actual value of the resistivity of the first resistivity $\rho_L$ of the electrode **17** and the second resistivity $\rho_H$ of the high resistivity region **18** will be application dependent, a typical resistivity of the electrode **17** will be in the micro-ohm-cm (μΩ-cm) range. In contrast, in order to generate a significant amount of the joule

heat $\mathbf{J}_H$, a resistivity that is an order of magnitude (i.e 10x) or higher than the first resistivity $\rho_L$ of the electrode **17** is preferable for the second resistivity $\rho_H$ of the high resistivity region **18**.

Plasma processes that are well understood in the microelectronics art can be used to compositionally modulate (i.e. increase the resistivity) the material of the electrode **17** to form the high resistivity region **18**. For example, a plasma oxidation process that generates a gas plasma in a carrier gas that includes oxygen ($\mathbf{O_2}$) can be used to form the high resistivity region **18**. As another example, a plasma nitridation process that generates a gas plasma in a carrier gas that includes nitrogen ($\mathbf{N_2}$) can be used to form the high resistivity region **18**. As yet another example, a plasma carburization process that generates a gas plasma in a carrier gas that includes carbon (**C**) can be used to form the high resistivity region **18**. Compounds other that the oxygen ($\mathbf{O_2}$), the nitrogen ($\mathbf{N_2}$), and the carbon (**C**) can be included in the carrier gas for the respective plasma processes. As an example, for plasma nitridation, the carrier gas can be the nitrogen ($\mathbf{N_2}$) itself or the carrier gas can be argon (**Ar**) mixed with an ammonia ($\mathbf{NH_3}$). As another example, for plasma carburization, the carrier gas can be argon (**Ar**) mixed with a carbon containing gas, and for plasma oxidation, the carrier gas can also be argon (**Ar**) mixed with oxygen ($\mathbf{O_2}$).

In **FIG. 10a** and referring to a method of fabricating a compositionally modulated electrode in a magnetic tunnel junction device depicted in **FIG. 8**, at a stage **82**, an alloy layer **22** is deposited on a surface **17s** of a previously fabricated electrode **17** of a magnetic tunnel junction device **10**. The electrode **17** includes the first resistivity $\rho_L$. As was described above, the various thin film layers of material that comprise the magnetic tunnel junction device **10** (i.e. **11, 13, 15, 17, 17v, 19**, **21** and **31**) have been previously fabricated in a process order $\mathbf{D_O}$ and those layers are collectively denoted as the stack **20**. Deposition processes including but not limited to sputtering, atomic layer deposition (ALD), chemical vapor deposition (CVD), and plasma enhanced chemical vapor deposition (PECVD) can be used to form the alloy layer **22**. The alloy

layer **22** can be made from an electrically conductive material and the electrically conductive material can include but is not limited to a metal, a metal alloy, and a semiconductor material.

In **FIG. 10a**, at a stage **84**, a mask layer **35** is deposited on the alloy layer **22**. As was described above, the mask layer **35** can be a photoresist material that is deposited on a surface **22s** of the alloy layer **22**. At a stage **86**, the mask layer **35** is patterned to form an etch mask (not shown) on the alloy layer **22**. In **FIGS. 10a** and **10b**, the patterning can include exposing the photoresist material of the mask layer **35** with a light **L** through a photo mask (not shown), and then developing or etching the photoresist material to form an etch mask **37**on the alloy layer **22**. The etch mask **37** protects those portions of the alloy layer **22** that are covered by the etch mask **37** from being removed during a subsequent etch process.

In **FIGS. 10b** and **10c**, at a stage **88**, the alloy layer **22** is etched **E** to form an alloy patch **24** on the surface **17s** of the electrode **17**. Preferably, an anisotropic/directional etching process such as a reactive ion etch (RIE) is used for the etching at the stage **88**. At a stage **90**, the etch mask **37** is removed from the alloy patch **24**. For example, a solvent or a plasma ashing process can be used to remove the etch mask **37**.

In **FIG. 10d**, at a stage **92**, an alloying of the alloy patch **24** with the electrode **17** results in a forming of a high resistivity region **18** in the electrode **17**. The alloying results from a heat $H_A$ being applied to the alloy patch **24** and the electrode **17** and the alloying creates a high resistivity region **18** that extends inward of the surface **17s**. The high resistivity region **18** includes the second resistivity $\rho_H$ that is higher than the first resistivity $\rho_L$.

The actual alloying temperatures and times will be application and material dependent; however, the temperature used should not exceed a value that would cause a degradation of the magnetic materials used in the stack **20** of the magnetic tunnel junction **10**. As an example only, typically the temperature used for the alloying at the stage **92** should not exceed a range from about 450 °C to about 500 °C.

In **FIG. 10e**, the alloying of the alloy patch **24** with the electrode **17** can continue until the high resistivity region **18** extends inward of the surface **17s** by the predetermined depth $\mathbf{d_O}$ as was described above. Alternatively, the alloying process that forms the high resistivity region **18** can be continued until the second resistivity $\rho_H$ of the high resistivity region **18** reaches a predetermined value of resistivity.

In **FIGS. 9e** and **10f**, as was described above, the stack **20** can include a second electrode **21** that can serve as one of the write lines during a write operation to the data layer **11**. For instance, the electrode **17** and the second electrode **21** can be write conductors for writing data to the data layer **11** during a write operation and the electrode **17** and the first electrode **19** can be column and row conductors used for sensing the state of the data layer **11** during a read operation.

Suitable materials for the electrode **17**, the first electrode **19**, the second electrode **21**, the via **17v**, the alloy layer **22**, and the alloy patch **24** include but are not limited to aluminum (**Al**), tungsten (**W**), and copper (**Cu**). A resistivity of those materials can be increased (i.e. to form the second resistivity $\rho_H$ for the high resistivity region **18**) by doping with materials including but not limited to nitrogen ($\mathbf{N_2}$), oxygen ($\mathbf{O_2}$), and carbon (**C**).

As an example, the electrode **17** can be made from doped polysilicon (**α-Si**) or a silicide (i.e. a metal and silicon compound). A resistivity of the polysilicon can be increased (i.e. to form the second resistivity $\rho_H$ for the high resistivity region **18**) by increasing a doping concentration of the electrode **17** at the high resistivity region **18**.

A resistivity of the silicide can be increased by varying a composition of the silicide by adjusting a metal to silicon (**Si**) ratio of the silicide.

As another example, the alloy layer **22** and the alloy patch **24** can be made from a doped glass including but not limited to a doped tetraethylorthosilicate (**TEOS**) such as a boron (**B**) doped tetraethylorthosilicate (**BSG**), a phosphorus (**P**) doped tetraethylorthosilicate (**PSG**), and a boron (**B**) and phosphorus (**P**) doped tetraethylorthosilicate (**BPSG**). Accordingly, if the alloy patch **24** is a doped glass, then the electrode **17** can be made from polysilicon (**α-Si**), for example. On the other hand, if the alloy patch **24** is made from polysilicon (**α-Si**), then the electrode **17** can be made from a silicide, for example.

Although several embodiments of the present invention have been disclosed and illustrated, the invention is not limited to the specific forms or arrangements of parts so described and illustrated. The invention is only limited by the claims.